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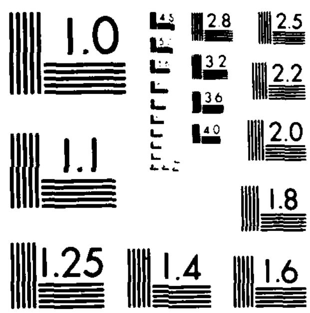

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Attention: Dr. J. Bram, Program Manager

For:
AFOSR [redacted] 82-0304

Principal Investigator:
Izhak Rubin
Professor
Electrical Engineering Department

Co-Principal Investigator:
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Associate Professor
Computer Science Department

UCLA-ENG-83-47

PERFORMANCE EVALUATION AND CONTROL OF DISTRIBUTED COMPUTER COMMUNICATION NETWORKS

University of California, Los Angeles
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During the 1982/83 first year performance-period under this AFOSR Grant, we have carried out research investigations and obtained many significant results of both theoretical and practical importance. A large multitude of computer communication network architectures, models and control schemes have been developed, analyzed and evaluated. In particular, results have been obtained in the following areas: priority-based TDMA schemes; dynamic random-access procedures, with applications to local area networks and to local distribution and packet-radio networks; hybrid multiple-access schemes; polling, adaptive poll-

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"PERFORMANCE EVALUATION AND CONTROL
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ABSTRACT

During the 1982/83 first year performance-period under this AFOSR Grant, we have carried out research investigations ~~and obtained~~ many significant results, of both theoretical and practical importance. A large multitude of computer communication network architectures, models and control schemes have been developed, analyzed and evaluated. In particular, results have been obtained in the following areas: priority-based Time Division Multiple Access ~~TDMA~~ schemes; dynamic random-access procedures, with applications to local area networks and to local distribution and packet-radio networks; hybrid multiple-access schemes; polling,adaptive polling and probing access-control techniques; buffer capacity constrained multi-access systems; network topological analysis; local area network topological analysis; local area network protocols; integrated packet and circuit networks; integrated routing and flow control.

I. INTRODUCTION AND SUMMARY

During the 1982/83 year, being the first year performance period under this AFOSR Grant, we have carried out research investigations and obtained many significant results, of both theoretical and practical importance. A large multitude of computer communication network architectures, models and control schemes have been developed, analyzed and evaluated.

Results have been obtained in the following areas:

1. Performance Analysis for Priority-Based TDMA Schemes for Multi-Access Communication Networks.
2. Performance Evaluation and Control of Dynamic Random-Access and Hybrid Multiple-Access Schemes.
3. Performance Analysis of Polling, Adaptive-Polling and Probing/Reservation Schemes.
4. Performance Analysis and Control of Buffer-Capacity Constrained Multi-Access Systems.
5. Topological Analysis and Design of Survivable Communication Networks.
6. Local Area Network Architectures and Protocols for the Integration of Data/Voice/Video.
7. The Analysis and Design of Hybrid Packet and Circuit Switched Networks.
8. Integration of Routing and Flow Control Algorithms in Computer Networks.

These research studies have been carried-out by the Principal Investigators, Professors Izhak Rubin and Mario Gerla, with the participation of a number of Ph.D. students, including: L. Clare, L.A. De Moraes, J. Baker, M. Zuckerman, S. Katz, P. Rodrigues, R. Pazos, S. Resheff. Other participants are the following visiting researchers: Dr. Luis F. De Moraes

and Dr. J. Hartman, working jointly with Professor I. Rubin; and Dr. Boisson, working jointly with Professor M. Gerla.

Results of the investigations have been presented in Conferences, and submitted for publication in the top journals in the field, as indicated in the Publications section. Many of the underlying research topics are currently being further developed and investigated by us.

II. DESCRIPTION OF RESEARCH INVESTIGATIONS

1. Performance Analysis for Priority-Based TDMA Schemes for Multi-Access Communication Networks

Multiple-access communications channels are used to provide network communications in most utilized distributed computer communication networks. The multi-access channel is shared among a number of, many times diverse, data sources and sinks. The channel access-control (multiple-access) scheme provides for the coordination, supervision and control of the joint sharing of the multiple-access communications channel. The access-control scheme needs to be designed such that it efficiently allocates the limited communications channel resources (time, bandwidth, space and power) under prescribed grade-of-service constraints. Typically, the performance of the multiple-access control procedure is measured in terms of the ensuing delay-throughput performance function. The latter describes the behavior of the message-delay as a function of the channel (or network) throughput. Message delay measures are amended or replaced by blocking probability indices when buffer capacity limitation and/or non-queued assignment disciplines are invoked (as described in Area 4).

Among the key access-control disciplines employed to control the

sharing of a multiple-access channel are the Fixed-Assignment TDMA (Time-Division-Multiple-Access) and FDMA (Frequency-Division-Multiple-Access) schemes. Under a TDMA scheme, each network station is allocated periodic time slots during which it can transmit its ready messages. When transmitting, the station occupies the whole channel bandwidth. TDMA schemes allow considerable flexibility in providing multiple-access communications to diverse information sources, and are thus widely used.

Under an FDMA scheme, each network station is allocated a dedicated frequency band. Limited to this band, a station can continuously transmit its ready messages. FDMA schemes have been inexpensively implemented and are therefore also widely used.

TDMA and FDMA schemes are specially efficient in supporting stations which generate steady traffic streams. Other multiple-access schemes are employed to support stations which generate traffic in a bursty, low duty-cycle fashion. Random-access and Polling schemes provide such efficient control for lower network throughput levels, as noted in Areas 2 and 3. At medium to high traffic levels, reservation schemes (and Polling procedures, when the Walk Time is short, see Area 3) provide efficient coordination of the multi-access network.

Under a Reservation scheme, ready stations transmit first a reservation packet which designates their needs for channel transmission service. Transmission slots across the channel are then allocated according to these requests, on a first-come first-served (FCFS) or priority basis. The allocation can be performed in a centralized or fully distributed fashion.

Our research investigations, supported by this Grant over the period

starting at 6/30/82, have already yielded important results in this area. In particular, the following priority model has been applied. Messages are categorized as belonging to one of two priority classes. (Extensions to more than two priority classes would then be carried out, directly based on the above results.) Priority-1 messages are designated higher priority than Priority-2 messages. Two basic priority service disciplines are assumed:

1. Non-preemptive: Priority-1 messages are served prior to priority-2 messages, but an on-going priority-2 message transmission cannot be interrupted.

2. Preemptive-resume: Priority-1 messages are served prior to priority-2 messages; if a priority-1 message arrives during the transmission of a priority-2 message, it waits until the current message sub-block (called packet) ends its transmission, and it subsequently interrupts the priority-2 transmission; the latter message transmission later resumes with the transmission of the subsequent message blocks, so that channel capacity is not wasted.

The above priority-based multiple-access systems are modeled as priority discrete-time queueing systems with proper message batch streams and multiple-packet message (service) lengths. The arrival streams of each priority class are assumed to be general independent stochastic point processes, of which Poisson processes constitute a special case. We have derived message delay steady-state distributions for these schemes. For these systems, no message delay results currently exist in the queueing literature or in the computer communications research literature. Further note that the special structure of a TDMA system induces a specially time-

interrupted service (transmission) process. We have also obtained queue-size distributions, describing the statistical fluctuations of the station buffer packet occupancy process. As derived by us previously for non-priority systems, we have further derived statistical characterizations of the delay difference between priority-based FDMA and TDMA schemes.

The results we have derived under such a discrete-time priority TDMA model, based on investigations supported by this Grant, are presented in [1].

We have also obtained results, based on studies performed under this Grant, for message delay distributions for a TDMA scheme, under a Non-Preemptive continuous-time based priority discipline [2]-[3]. Under this model, the arrival and message-length processes are discrete-time, as assumed in [1]. However, while messages arriving within the same frame, and *belonging to the same priority* class, are served at random order under the model in [1], we assume a first-come first-served discipline for such messages in [2]-[3]. We have developed a simple but powerful analytical technique, which was used to derive the moment-generating-function of the message delay distribution. The latter function has been used then to derive message delay moments.

We have received preliminary results for such TDMA systems in [4]-[6]. In these studies, we have derived analytical procedures that provide for queue-size and message delay calculations for TDMA schemes, under prescribed buffer capacity limitations. These results are of significant importance in carrying out performance analysis for many practical multiplexing and multiple-access multi-user communication channels, with critical buffer capacity limitations.

Using Markov-Renewal stochastic process models, we also derive the distribution of the queue-size and message delay functions over the TDMA frame.

2. Performance Evaluation and Control of Dynamic Random-Access and Hybrid Multiple-Access Schemes

Random-access schemes provide a simple mechanism for efficiently sharing a multiple-access communications channel among bursty, low duty-cycle, terminals. Interactive computer terminals and packet-oriented information sources (such as those which dominate packet communications in military networks) serve as examples of widely-used terminals which generate bursty traffic streams. Under a random-access scheme, a ready packet is transmitted across the channel at proper time, as determined by the access-control scheme, with no or minimal coordination among the transmitting terminals. As a result, at certain times messages may collide (by being transmitted at the same time) and consequently destroyed. Colliding messages are then retransmitted after a random delay, as determined by the governing access-control algorithm.

A number of random-access procedures have been proposed, investigated and implemented. Previously, I. Rubin introduced the Group-Random-Access (GRA) scheme. Under this scheme, a group of the network stations which wish to share the multiple-access channel on a random-access basis, is allowed to transmit their ready packets within designated periodically recurring time-periods. Colliding packets are retransmitted in a subsequent time-period, at a randomly chosen slot.

The GRA procedure entails a number of significant advantages:

1. It is simple to implement.

2. It readily permits the implementation of a hybrid access-control procedure, under which different network groups employ different access-control algorithms, to match their own traffic statistics and grade-of-service needs.

3. It allows the implementation of a multi-priority station group hierarchy.

4. The scheme incorporates a simple control mechanism, which makes it stable.

We have extended the structure of GRA schemes to allow dynamic adaptation in the procedural structure. The scheme would then adapt its time-period structure to correspond to the underlying channel traffic, as observed by the network users through their recordings of the numbers of collisions and successful transmissions within each period. In addition, Channel-Sense GRA schemes have been developed and analyzed. The resulting dynamic schemes yield substantial performance improvements.

We have developed in [7]-[8] such an adaptive random-access procedure, called Dynamic Group-Random-Access (DGRA) scheme. We have also carried out preliminary throughput and message-delay performance analysis studies for DGRA schemes. Synchronous as well as asynchronous channel-sense structures have been incorporated. We have shown such schemes to yield excellent delay-throughput performance characteristics for local-area and local-distribution networks, under various channel/equipment/system conditions. In particular, channel-sense asynchronous DGRA schemes have been shown to exhibit superior performance as access-control schemes for half-duplex broadcast local distribution systems, such as those involved in military packet-radio and mobile data radio communication networks.

We also have continued our investigations of Hybrid access-control policies. Hybrid schemes need to be implemented in many military and commercial networks to allow acceptable grade-of-service levels and efficient channel bandwidth sharing, when:

1. The network stations are of heterogeneous nature, being characterized by distinct statistical traffic processes and grade-of-service requirements.
2. The underlying network traffic characteristics statistically fluctuate with time, so that certain access-control algorithms are efficient at certain times, while at other times different algorithms must be employed to provide acceptable communications support.

We have recently developed and analyzed in [9]-[10] a hybrid TDMA/Random-Access Multiple-Access (HTRAMA) scheme. This scheme incorporates both TDMA and Random-Access protocols. The structure of the scheme is dynamically adapted to assume the best TDMA/Random-Access proportion so that it yields the best delay-throughput behavior for the underlying estimated network traffic conditions. In this fashion, the scheme provides a stable operation and exhibits good message delay levels over the whole throughput range.

3. Performance Analysis of Polling, Adapative-Polling and Probing/Reservation Schemes

Polling schemes are widely used in data communication networks to provide multiple-access and multiplexing control. Under a polling procedure, a central station (nominated as the central controller) queries in-turn the network stations. Upon receiving a query message, a station

either transmits its ready message, or responds with a "no-message" reply. Thereafter, the next network station is queried.

A number of performance analysis papers for polling schemes have been published. However, these papers derive only results for the queue-size distribution, and obtain subsequently as estimate of the message waiting time (in the form of a "virtual waiting-time").

Pure polling schemes induce long message delays when long "walking-times" (time required to propagate the transmit query and response packets) are experienced, and when low duty-cycle terminals need to be supported, under low or medium throughput levels. Better channel utilization and grade-of-service levels are then attained when probing/reservation polling schemes are used. Such schemes used proper probing of sets of network stations to provide access to the underlying multi-access channel. In a distributed control environment, the probing procedure is replaced by a reservation process.

We have developed techniques to analyze such a probing/reservation scheme which uses a Tree-Random-Access algorithm to provide access to status (reservation) messages transmitted by the active network stations. Such a control algorithm, which can be implemented in a centralized or distributed fashion, is shown to be easily implementable and to yield good message delay and throughput performance characteristics. Under this Grant, we have further developed and analyzed such Polling, and Probing/Reservation schemes [11]-[12].

4. Performance Analysis and Control of Buffer-Capacity Constrained Multi-Access Systems

We have studied multiple-access systems that are buffer capacity

constrained. In these systems, due to limitations imposed by the limited capacity of the data storage facilities, buffer overflows can occur. It is thus required to evaluate the probability of overflow, or the probability of message blocking (in preventing such overflow).

As noted in Area 1, we have recently derived results for limited buffer capacity multiple-access systems that employ TDMA controls. We have also been developing methodologies to categorize the realizable multi-dimensional regions of blocking probabilities for such systems, when general priority-based control disciplines are employed. These results should be of significant interest to the network designer and analyst, in allowing him to assess what levels of blocking probabilities can be realized, for each priority message class, and what the characteristics are of policies to be used for their implementation.

We have recently obtained such initial results, through investigations supported by this Grant, in [13]. We have considered there systems in which many data sources are multiplexed over a single communication channel, through a buffer with limited capacity. We characterize the admissible set of all possible performance vectors, as we span the set of all queueing service disciplines.

5. <u>Topological Analysis and Design of Survivable Communication Networks</u>

It is of key importance for many military and commercial applications, to ensure that a communication network topology attains a high degree of survivability under nodal/line failures. For such an analysis, the network structure is typically represented as a graph, and its invulnerability is expressed in terms of a graph-theoretical connectivity

index. Furthermore, it is important to design the network topological structure such that it ensures, at the same time, a high degree of survivability (connectivity), and an acceptable grade-of-service level (such as message delay), under a limited amount of total resources such as total communication network bandwidth. Such models and analysis and design methodologies have been developed by Dr. Rubin in a paper published in IEEE Trans. on Communications, Jan. 1978. In this paper, the network survivability is expressed by the graph connectivity, the message delay measure is related to the graph diameter, and the overall network capacity (bandwidth) level is represented by the number of lines of the graph.

It is of further importance to guarantee that under node or line failures, the network will not only continue to operate, but that it will operate at an acceptable grade-of-service level. For that purpose, using a graph theoretical model, the notion of diameter-stability was defined by Dr. I. Rubin and Dr. J. Hartman in a recent paper. The latter measure ensures that under a certain number of node/line failures, the diameter of the graph (the message delay across the network) will not increase beyond a specified level. Such survivability and diameter-stability measures are of key importance in the analysis and synthesis of communication network topologies.

During Fall 1982, Dr. I. Rubin and Dr. J. Hartman, supported by this Grant, carried out further investigations in this area. Models have been evaluated for examining various network survivability and diameter stability issues [14]. In addition to the graph models mentioned above, the graph theoretical concept of domination has been consider-

ed for application to carious aspects of communication network topological survivability.

6. Local Area Network Architectures and Protocols for the Integration of Data/Voice/Video.

In the area of local integrated networks most of our interests have been directed to bus architectures. We have recognized that the most popular local bus access protocol, Ethernet, suffers of various limitations when used for integrated traffic. Most importantly, it performs poorly at the very high bandwidth x length products (say > 1Gbpsxkm) that may be required for real time applications; and it does not guarantee delivery delays within the tolerances often required by real time traffic. On this subject, the paper "Tokenet: A Token Based Bidirectional Network" was presented at the Melecon Confernece, Athens, Greece, May 1983 [15]. The paper descrives the architecture of a high data rate bus structured local area computer network based on a deterministic multiple access protocol. The dynamic sharing of the available bandwidth among stations is achieved by forming "trains" to which each station may append a packet after issuing a reservation. Reservations and packet transmissions are governed by the reception of short control packets named tokens issued by the network end stations. Algorithms for the election of the end stations, the recovery from failures, and the insertion of new stations in the network are presented. They are all based on the use of special tokens. The network performance is evaluated, and it is shown to be similar to that of EXPRESS-type networks. Advantages with respect to L-EXPRESS networks are the simpler organization and implementation that result in a more robust protocol. In comparison to Ethernet-like net-

works, TOKENET offers a much higher efficiency at high data rates and a stable protocol.

We also have studied the possibility of implementing the token protocol to unidirectional bus architectures. This study was motivated by the interest in achieving extremely high bus speeds (on the order of the gigabit per second), which are feasible only with optical fibers. Since the optical fiber bus is intrinsically unidirectional when passive taps are used, the only bus architectures that lend themselves to fiber implementation are the unidirectional ones. Among the various architectures that we examined is the two parallel, unidirectional bus configuration. A token circulates alternatively from one bus to the other, enabling stations to transmit in a collision free, round robin mode. The token protocol for the two bus scheme is described in the paper "A Token Protocol for High Speed Fiber Optics Local Networks" presented at the Optical Fiber Communications meeting (OFC '83), New Orleans, Louisiana, March '83 [16].

7. The Analysis and Design of Hybrid Packet and Circuit Switched Networks

In the area of hybrid packet and circuit switching systems we have dedicated most of our efforts to the study of express pipe networks. An express pipe is a physical circuit established between an arbitrary source/destination pair in a hybrid network and used to transfer packets transparently (i.e., without need of buffering, reassembly and queueing at intermediate nodes) from source to destination. An express pipe network is a network in which each node pair is connected by one of more express pipes. The main advantages of express piping are the reduction of node delay and node processing overhead due to the fact that packets travel

directly from source to destination without being inspected nor queued at intermediate nodes. One drawback of express piping is the reduction in bandwidth sharing and flexibility caused by the preallocation of network bandwidth to pipes.

Two problems concerning the design of express pipes have been addressed: (1) Optimal Bandwidth Allocation and (2) Optimal Routing. The first problem consists of finding the best allocation of trunk bandwidth given that the express pipe layout and the distribution of traffic among parallel pipes are known. The objective function is the average packet delay. The constraints are the trunk capacities. The problem can be shown to be convex (i.e. convex objective over a convex constrained set). Therefore, a straightforward steepest descent procedure leads to the global minimum.

The optimal routing problem consists of finding the best distribution of packets over a predefined express pipe network (i.e., pipe layout and bandwidth are given). Again, the objective is the average packet delay. The problem is shown to be very similar to the optimal routing in a packet switched network. The original topology is replaced with a "second order" topology and the Flow Deviation algorithm is applied to the latter to obtain the optimal routing solution.

In this area, the paper "Express Pipe Networks," was presented at the GLOBECOM Conference, Miami, December 1982 [17]. Express pipe networks can reduce packet end-to-end delay, and storage and processing overhead. Therefore, the substitution of packet switched subnets by express pipe subnets can enhance the performance of integrated packet/circuit switched networks. Three problems concerning the design of express pipe

networks are addressed: (1) Optimal Bandwidth Distribution, (2) Optimal Routing, and (3) Bandwidth Distribution and Routing. For each of these problems, we present its mathematical formulation, conditions for optimality, and an algorithm.

Still in the area of integrated networks the paper "Routing, Flow Control and Bandwidth Allocation in ISDN's" was prepared and submitted to the IEEE Communication Magazine [18]. The purpose of this paper is to present algorithms for the optimal design of ISDN's. First, to better understand integrated networks, three multiplexing systems that allow the integration of circuit and packet switching traffic are described. Then, two design problems — bandwidth allocation and routing for integrated networks and bandwidth allocation and routing for flow controlled networks — are discussed and efficient algorithms are presented for their solution.

8. Integration of Routing and Flow Control Algorithms in Computer Networks

Routing and flow control are two fundamental control procedures in computer networks. Routing is responsible for finding optimal paths and flow control is responsible for preventing congestion by regulating external inputs. It is important to coordinate the two activities so that they reinforce each other (instead of conflicting with each other). For example, at the network entry point, it is useful to know which paths are available in the network (i.e., routing information) before deciding whether to accept data for a given destination (flow control decision).

Flow control can be exercised by direct regulation of user input rates (input rate control) or by user window adjustment (window control).

Routing can be implemented using distributed or centralized algorithms. Finally, the objective of the optimization problem could be delay (to be minimized) or throughput (to be maximized) or some other performance measure which includes both delay and throughput.

In the past year most of our research has focused on a problem with window flow control, centralized routing and minimum delay as the objective function. We have succeeded in showing that a routing solution which minimizes the delay also maximizes the throughput. We also have shown that in the case of a single chain network (i.e., all the traffic has a common source and a common sink) the delay is a convex function of the flows. This result implies that a local minimum is also a global minimum. Thus, any descent technique can be used to find the optimal solution. A very efficient algorithm based on Mean Value Analysis and Flow Deviation was developed to find optimal routing solutions.

In this area, the paper "Optimal Routing in Closed Queueing Networks" was prepared for and accepted in the ACM Transactions on Computer Systems [19]. In this paper, we establish criteria and propose algorithms for the optimal routing of traffic in closed queueing networks. The objective is to maximize total throughput or (equivalently) to minimize overall average delay. We show that delay is convex over the set of routing patterns in networks with a single class of customers. This enables us to develop a downhill technique to find the global minimum. The efficiency of our algorithm rests on the fact that the steepest descent direction is readily obtained at each iteration from the MVA algorithm. For multiple class networks a counterexample is presented to show that convexity does not hold. The technique, however, can still be used to obtain local min-

ima. The algorithm is applied to the optimization of routing in flow controlled packet switched networks. Several numerical examples are presented.

Also, research was performed in the area of "fairness" in computer networks. A presentation titled "Computer Network Routing and Flow Control with Delay and Fairness Constraints" will be delivered at the ORSA/TIMS Conference in Orlando, Florida, November 1983. In a packet switched computer network if traffic demands exceed network capacity, the problem is said to be infeasible. In this case, flow control is applied to the inputs so that the traffic volume becomes manageable. In this process, however, unfairness may arise in that some users may be penalized more than others. In this paper, we propose a method for simultaneous selection of routes and regulation of flows so that fairness is maintained and a given delay constraint is met.

III. PUBLICATIONS

[1] I. Rubin, "Message Delay Analysis of Priority TDMA, FDMA and Discrete-Time Schemes for Multiple-Accesss Communications," IEEE Trans. on Inform. Theory, submitted for publication.

[2] I. Rubin, and L.F. De Moraes, "Message Delay Distributions for a TDMA Scheme under a Non-Preemptive Priority Discipline," Proc. GLOBECOM '82, Miami, Florida, November 1982.

[3] I. Rubin, and L.F. De Moraes, "Message Delay Analysis for a TDMA Scheme under a Non-Preemptive Priority Discipline," IEEE Trans. on Communications, submitted for publication.

[4] L.P. Clare and I. Rubin, "Queueing Analysis of TDMA with Limited and Unlimited Buffer Capacity," Proc. INFOCOM '83, San Diego, CA, April 1983.

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[6] L.P. Clare and I. Rubin, "Queueing Analysis of TDMA with Limited and Unlimited Buffer Capacity," IEEE Trans. on Information Theory, submitted for publication.

[7] I. Rubin, "Synchronous and Carrier-Sense Asynchronous Dynamic Group-Random Access Schemes for Multiple-Access Communications," Proc. GLOBECOM '82, Miami, Florida, November 1982.

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[9] I. Rubin and M.Y. Louie, "A Hybrid TDMA/Random-Access Scheme for Multiple-Access Communication Networks," Technical Report, UCLA School of Engineering and Applied Science, UCLA-ENG-8254, July 1982.

[10] I. Rubin and M.Y. Louie, "A Hybrid TDMA/Random-Access Scheme for Multiple-Access Communication Networks," Computers & Electrical Engineering, to be published, 1983.

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[12] I. Rubin and L.F. De Moraes, "Performance Analysis for an Adaptive Polling Access-Control Scheme Employing a Dynamic Reservation Protocol," IEEE Trans. on Communications, submitted for publication.

[13] L.P. Clare and I. Rubin, "Performance Boundaries for Prioritized Multiplexing Systems," Proc. Intl. Conference on Communications, Boston, MA, June 1983.

[14] J. Hartman and I. Rubin, "Communication Network Survivability: Diameter Stability and Domination of Graphs," Technical Report, UCLA School of Engineering and Applied Science, in preparation.

[15] M. Marsan, and M. Gerla, "Tokenet - A Token Based Bus Structured Local Area Network," Melecon Conference, Athens, Greece, May 1983.

[16] M. Gerla, Y. Cavour, and P. Rodrigues, "A Token Protocol for High Speed Fiber Optics Local Networks," OFC Conference, New Orleans, Louisiana, March 1983.

[17] R. Pazos and M. Gerla, "Express Pipe Networks." GLOBECOM Conference Proceedings, Miami, Florida, December 1982.

[18] M. Gerla, "Routing, Flow Control and Bandwidth Allocation in ISDN's," submitted to IEEE Communication Magazine.

[19] H. Kobayashi and M. Gerla, "Optimal Routing in Closed Queueing Networks," ACM Communications Architectures and Protocols Symposium, Austin, Texas, March 1983. Also in ACM Transactions on Computer Systems, 1983.